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Solving the Milky Way Satellite Problem with Interactions between Cold Dark Matter and Radiation

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ABSTRACT

The cold dark matter (CDM) model faces persistent challenges on small scales. In particular, the model significantly overestimates the number of satellite galaxies around the Milky Way. Attempts to solve this problem remain controversial and have even led some to abandon CDM altogether. However, current simulations are limited by the assumption that dark matter feels only gravity. Here we show that including interactions between CDM and radiation (photons or neutrinos) leads to a dramatic reduction in the number of satellite galaxies, providing a potential solution to the Milky Way satellite problem and indicating that physics beyond gravity may be essential to make accurate predictions of structure formation on small scales. The methodology introduced here gives constraints on dark matter interactions that are significantly improved over those from the cosmic microwave background.

Key words: galaxies: dwarf – galaxies: abundances – dark matter – large-scale structure of Universe.

1 INTRODUCTION

The need for ‘dark matter’ (DM) was initially inferred from the shape of galactic rotation curves and the dynamics of galaxies in clusters. Modern evidence now includes the pivotal role of DM in the formation of structure in the Universe (Frenk & White 2012). Although around 80 per cent of the matter content of the Universe is thought to be in the form of DM particles (Ade et al. 2013), these are yet to be discovered (Akerib et al. 2013).

N-body simulations of ‘cold’ dark matter (CDM) (consisting of weakly-interacting particles with a low velocity dispersion and therefore, negligible free-streaming) agree remarkably well with observations of the Universe on the largest scales (Davis et al. 1985). However, as the resolution of the simulations improved, significant discrepancies emerged on small scales. For example, DM halo profiles for dwarf galaxies are less cuspy than predicted by CDM (Dubinski & Carlberg 1991) (although this is still under debate, see Frenk & White 2012) and large CDM haloes do not form as many stars as expected (the ‘too big to fail problem’, Boylan-Kolchin et al. 2011).

Here we address the so-called ‘Milky Way satellite problem’ (Klypin et al. 1999; Moore et al. 1999), which describes the disagreement between the number of ‘satellite’ galaxies

in orbit around the Milky Way (MW) and the much larger abundance of DM subhaloes predicted by the CDM model.

Many explanations have been proposed to solve this problem. One approach is to argue that subhaloes either host very faint galaxies that are not picked up by current surveys or do not form galaxies at all due to astrophysical processes such as heating of the interstellar medium by supernovae (Benson et al. 2002; Simon & Geha 2007). Alternatively, since the DM halo mass has a significant impact on the expected number of satellites, one may argue that the severity of the problem depends upon the choice of MW halo mass, which remains difficult to determine (Wang et al. 2012).

A more drastic solution is to abandon CDM and instead consider ‘warm’ dark matter (WDM). In this scenario, one allows a small (but non-negligible) amount of free-streaming, which greatly reduces the expected number of satellites with respect to CDM (Lovell et al. 2013). Given that the free-streaming scale of a DM particle is typically governed by its mass and velocity distribution, the proposed WDM models require very light (\sim keV) particles. However, recent work suggests that such light candidates cannot simultaneously solve the small-scale problems of CDM and satisfy the particle mass constraints from the Lyman- α forest and other observations (Schneider et al. 2013; Viel et al. 2013).

Here we explore an alternative strategy that allows us solve the MW satellite problem without having to discard

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CDM. In standard N-body simulations, DM is represented as a collisionless fluid that responds only to gravity. However, it is entirely plausible (and indeed expected) that DM interacts through other forces, with various components of the Universe¹. Such interactions have been shown to suppress small-scale density fluctuations (Boehm et al. 2001, 2002, 2005; Boehm & Schaeffer 2005; Chen et al. 2002; Dvorkin et al. 2013) but the implications for the satellite galaxy abundance have not been studied.

In this letter, we therefore simulate the formation of large-scale structure in a Universe where DM interacts with photons or neutrinos, to determine whether such a coupling can solve the MW satellite problem. We focus on radiation as this dominates the energy density at early times and should therefore lead to the largest effect on DM primordial fluctuations. For the sake of illustration, we will study specifically a DM–photon coupling (hereafter referred to as γ CDM) but very similar effects are expected in the case of a DM–neutrino coupling (ν CDM). We will use these results to extract constraints on the DM–photon scattering cross section. The other small-scale problems of CDM will be addressed in forthcoming work (Schewtschenko et al. 2014).

The paper is organized as follows. In Sec. 2, we discuss the theoretical framework of interacting DM models. In Sec. 3, we provide details regarding the setup of our simulations. In Sec. 4, we present the results of our simulations and in particular, the effect on the satellite galaxy abundance. Conclusions are provided in Sec. 5.

2 INTERACTING DM

Regardless of the particle physics model, DM interactions beyond gravity result in an additional collision term in the corresponding Boltzmann equations. For γ CDM, the modified Boltzmann equations read:

$$\dot{\theta}_{\text{DM}} = k^2 \psi - \mathcal{H} \theta_{\text{DM}} - S^{-1} \dot{\mu} (\theta_{\text{DM}} - \theta_{\gamma}), \quad (1)$$

$$\dot{\theta}_{\gamma} = k^2 \psi + k^2 \left(\frac{1}{4} \delta_{\gamma} - \sigma_{\gamma} \right) - \dot{\mu} (\theta_{\gamma} - \theta_{\text{DM}}), \quad (2)$$

where θ is the velocity dispersion, k is the wavenumber, ψ is the (DM-dominated) gravitational potential, \mathcal{H} is the expansion rate of the Universe, δ is the density contrast and σ is the anisotropic stress potential² (Wilkinson et al. 2013).

The new interaction rate, $\dot{\mu}$, is the product of the scattering cross section, $\sigma_{\text{DM}-\gamma}$, and the DM number density, while the DM–photon ratio, S , ensures energy conservation. For simplicity, we take $\sigma_{\text{DM}-\gamma}$ to be constant (however, a temperature-dependent cross section has a similar impact) and assume that the interacting DM species accounts for the entire observed relic abundance.

This formalism provides an accurate estimate of the collisional damping scale associated with DM interactions in the linear regime (when the density fluctuations are small). However, one can understand the underlying physics by considering both the DM and radiation as interacting imperfect

fluids (Boehm et al. 2001; Boehm & Schaeffer 2005) leading to a damping scale:

$$l_{\text{cd},\gamma}^2 \sim \int_0^{t_{\text{dec}}(\text{DM}-\gamma)} \frac{\rho_{\gamma} c^2}{\rho \Gamma_{\gamma} a^2} dt, \quad (3)$$

where ρ_{γ} is the photon energy density, ρ is total energy density, Γ_{γ} is the total interaction rate of the photons (including all species in thermal equilibrium with them) and a is the cosmological scale factor.

Eq. (3) illustrates why interactions with radiation can lead to the suppression of small-scale power needed to solve the MW satellite problem. In the early Universe, photons and neutrinos were ultra-relativistic and constituted the bulk of the energy density. Hence, the numerator in Eq. (3) is large and fluctuations can be erased on the scale of small galaxies, depending on the strength of the interaction.

The consequences of DM interactions with radiation have been computed in the linear regime (Boehm et al. 2002; Sigurdson et al. 2004; Wilkinson et al. 2013, 2014). The γ CDM matter power spectrum is damped relative to that of CDM beyond a scale that depends on the interaction cross section. This is similar to the damping seen in WDM, except that in this case, instead of an exponential suppression, one obtains a series of oscillations with a power law modulation of their amplitude (Boehm et al. 2002). We can compare WDM and γ CDM models by choosing particle masses, m_{WDM} , and interaction cross sections, $\sigma_{\text{DM}-\gamma}$, that produce a damping relative to CDM at a similar wavenumber.

For γ CDM, the comparison with cosmic microwave background (CMB) data from *Planck* (Ade et al. 2013) gives a constraint on the (constant) elastic scattering cross section of $\sigma_{\text{DM}-\gamma} \lesssim 10^{-6} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$, where σ_{Th} is the Thomson cross section and m_{DM} is the DM mass (Wilkinson et al. 2013). However, this linear approach breaks down once the fluctuations become large, preventing one from studying the effects of weak interactions on DM haloes and in particular, on small-scale objects.

3 SIMULATIONS

To study small-scale structures in these models, we begin our N-body calculations at a sufficiently early epoch ($z = 49$), where the effect of γ CDM is fully described by linear perturbation theory. The initial matter power spectra are obtained from a modified version of the Boltzmann code CLASS (Lesgourgues 2011), using the best-fitting cosmological parameters from *Planck* (Ade et al. 2013). Initial conditions are created using a second-order LPT code (Crocce et al. 2012).

To make predictions in the non-linear regime, we run a suite of N-body simulations using the code GADGET-3 (Springel 2005). To provide a suitable dynamical range, we perform simulations in both a large box ($100 h^{-1}$ Mpc, 512^3 particles) and a high-resolution small box ($30 h^{-1}$ Mpc, 1024^3 particles). A subset of simulations is re-run in a high-resolution large box ($100 h^{-1}$ Mpc, 1024^3 particles) to confirm the convergence scale. By comparing the results from different runs, we find that our calculations are reliable for subhaloes with $V_{\text{max}} \gtrsim 8 \text{ km s}^{-1}$. Gravitational softening is set to 5 per cent of the mean particle separation. For WDM particles with masses larger than $\sim \text{keV}$, the thermal velocities are sufficiently small that one can safely neglect the

¹ We do not study self-interactions as these have been discussed already in Rocha et al. (2013).

² We use the Newtonian gauge, where the Thomson scattering terms are omitted for brevity.

free-streaming in the non-linear regime without introducing a significant error on the scales of interest (Colín et al. 2008).

To quantify the impact of γ CDM on MW satellites, one needs to define criteria to select haloes that could host the MW. The most crucial condition is the DM halo mass. Motivated by calculations that attempt to reconstruct the MW mass distribution based on the measured kinematics of the observed satellites and stars (Xue et al. 2008; Boylan-Kolchin et al. 2013; Piffl et al. 2013), we consider DM haloes to be MW-like if their mass is in the range $(0.8 - 2.7) \times 10^{12} M_\odot$.

The second criterion we apply is based on environment. The MW appears to be located in an unremarkable region away from larger structures such as the Virgo Cluster and the major filaments feeding the Centaurus Cluster (Courtois et al. 2013). We therefore reject candidates with similar-sized haloes within a neighbourhood of 2 Mpc. The resulting sample of MW-like haloes is then divided into several subsets based on their virial halo mass. Haloes are identified using a friends-of-friends (FoF) group finder (Davis et al. 1985) with a linking length of 0.2 times the mean particle separation and subhaloes are identified using SUBFIND (Springel et al. 2001).

4 RESULTS

Fig. 1 shows the simulated distribution of DM in a MW-sized DM halo. For CDM (top-left panel), there is a large abundance of subhaloes within the DM halo, which illustrates the MW satellite problem. The bottom-left panel shows the same halo in a simulation of γ CDM, in which the interaction cross section is $\sigma_{\text{DM}-\gamma} = 2 \times 10^{-9} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$. The subhalo population is significantly smaller for this model compared to CDM. However, the suppression of subhaloes in γ CDM is too strong if we consider $\sigma_{\text{DM}-\gamma} = 10^{-7} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$ (bottom-right panel), which just satisfies the limit from the CMB (Wilkinson et al. 2013). Therefore, by adjusting the magnitude of the scattering cross section, not only is there scope to solve the MW satellite problem, but we can also place a more stringent constraint on the γ CDM interaction strength.

For the model of γ CDM with $\sigma_{\text{DM}-\gamma} = 2 \times 10^{-9} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$, the distribution of density fluctuations in the linear regime is similar to that of a WDM particle with a mass of 1.24 keV (top-right panel). However, the suppression of small-scale power in γ CDM is less extreme than in generic WDM models due to the presence of oscillations in the power spectrum, which offers a way to distinguish these two scenarios (and possibly provide a solution to the ‘too big to fail’ problem).

For more quantitative estimates, the cumulative number counts of MW satellites are plotted in Fig. 2 as a function of their maximal circular velocity. The simulation results are obtained by averaging over the haloes that satisfy the selection criteria outlined above. The left-hand panel shows predictions for the CDM model, with no interactions, in which the predicted number of subhaloes of a given maximum circular velocity greatly exceeds the observed number of MW satellites. The middle panel shows the results for $\sigma_{\text{DM}-\gamma} = 2 \times 10^{-9} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$, where there is a good match to the observed number of satellites.

Thus, we see that γ CDM with a small cross section provides a solution to the MW satellite problem. Finally, the right-hand panel of Fig. 2 shows the model of γ CDM with $\sigma_{\text{DM}-\gamma} = 10^{-7} \sigma_{\text{Th}} \times (m_{\text{DM}}/\text{GeV})$ and clearly, there are not enough small structures remaining in this case.

We can therefore constrain the interaction cross section by comparing the observed and predicted numbers of substructures. The uncertainties in the simulation results are derived from the spread in the sample set (for each host halo mass bin). A given model is ruled out if the number of predicted subhaloes is smaller than the observed number, within the combined uncertainties of these observables (see Fig. 3, top panel). From this, we conclude that the cross section cannot exceed $\sigma_{\text{DM}-\gamma} = 8 \times 10^{-9} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$ (at 2σ CL). Note that using the highest mass bin $(2.3 - 2.7) \times 10^{12} M_\odot$ provides us with the most conservative limit. Smaller MW-like halo masses (see Fig. 3, bottom panel) result in stronger upper bounds on the cross section as these haloes host fewer satellites.

5 CONCLUSIONS

We have shown that studying the formation of cosmic structure, particularly on small scales, provides us with a powerful new tool to test the weakly-interacting nature of DM. By performing the first accurate cosmological simulations of DM interactions with radiation (in this case, photons), we find a new, potential solution to the MW satellite problem, without the need to abandon CDM. The resulting constraints on the interaction strength between DM and photons are orders of magnitude stronger than is possible from linear perturbation theory considerations. Similar results are expected in the case of DM-neutrino interactions.

It should be noted that the observed value of V_{max} may be underestimated by our approach of directly calculating it from the stellar velocity dispersion (Bullock 2010). Combined with an expected increase in the number of satellites from additional completeness corrections, this would lead to even stricter constraints on the interaction cross section. A future paper will present the non-linear structure formation for such models in greater depth to examine whether one can solve the other small-scale problems of CDM (Schewtschenko et al. 2014).

Recent simulations with DM and baryons have shown that baryonic physics can alter the appearance of the subhalo mass function (Sawala et al. 2014). A definitive calculation would include the full impact of these effects, in particular, supernovae feedback and photoionization heating of the interstellar medium, but this is deferred to a future paper.

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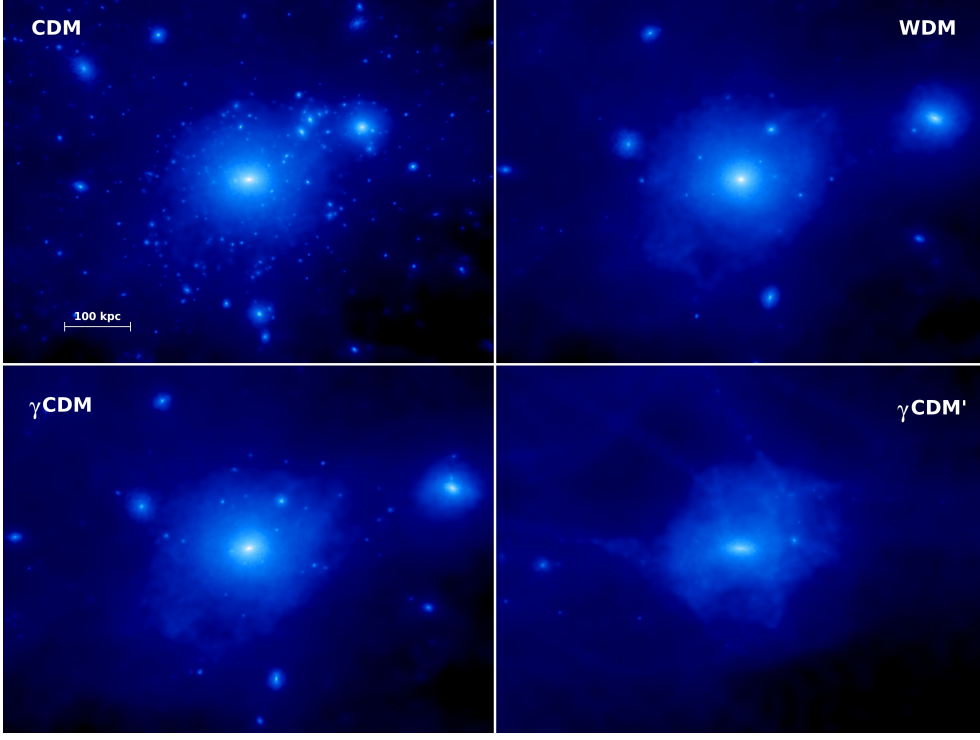


Figure 1. The simulated distribution of DM in a MW-like DM halo. The colour shading represents the logarithm of the DM density, with brighter colours indicating higher densities. The panels show how the halo appears in simulations of different cosmological models: CDM (top-left), γ CDM with $\sigma_{\text{DM}-\gamma} = 2 \times 10^{-9} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$ (bottom-left), the equivalent model of WDM with $m_{\text{DM}} = 1.24 \text{ keV}$ (top-right) and γ CDM with $\sigma_{\text{DM}-\gamma} = 10^{-7} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$ (bottom-right). The large number of subhaloes observed in the top-left panel illustrates the MW satellite problem. By replacing CDM with WDM (top-right), the number of subhaloes is reduced dramatically. A similar paucity of subhaloes is seen in the bottom-right panel, in which the DM–photon interaction strength is just allowed by CMB constraints (Wilkinson et al. 2013). This model underestimates the number of MW satellites. The model in the bottom-left panel has an interaction strength that is 1000 times smaller than the CMB limit, in which the number of subhaloes is a much better match to the observed number of satellites.

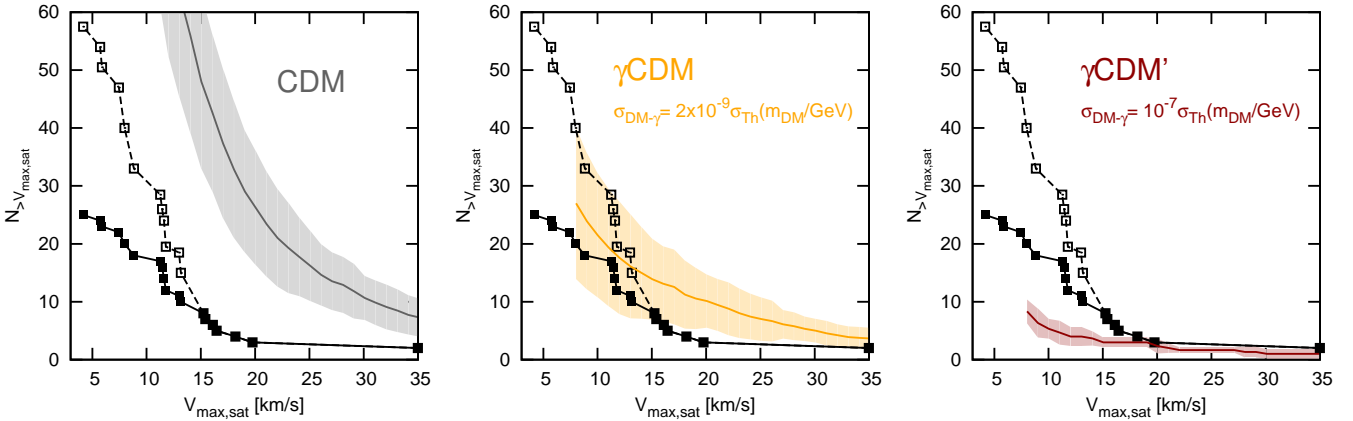


Figure 2. The number of satellite galaxies in a MW-like DM halo as a function of their maximal circular velocity: CDM (left), γ CDM with $\sigma_{\text{DM}-\gamma} = 2 \times 10^{-9} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$ (middle) and γ CDM with $\sigma_{\text{DM}-\gamma} = 10^{-7} \sigma_{\text{Th}} (m_{\text{DM}}/\text{GeV})$ (right). The lines and shading show the mean cumulative number counts of MW satellites for a simulated DM halo in the mass bin $(2.3 - 2.7) \times 10^{12} M_{\odot}$ and the 1σ uncertainty. Also plotted are the observational results (Willman 2010) (solid black lines), which are then corrected for the completeness of the Sloan Digital Sky Survey coverage (dashed lines). The maximal circular velocity, V_{max} , is selected as a measure for the mass and is determined directly from the simulations (it is derived from the observed stellar line-of-sight velocity dispersions using the assumption that $V_{\text{max}} = \sqrt{3}\sigma_{*}$, Klypin et al. 1999).

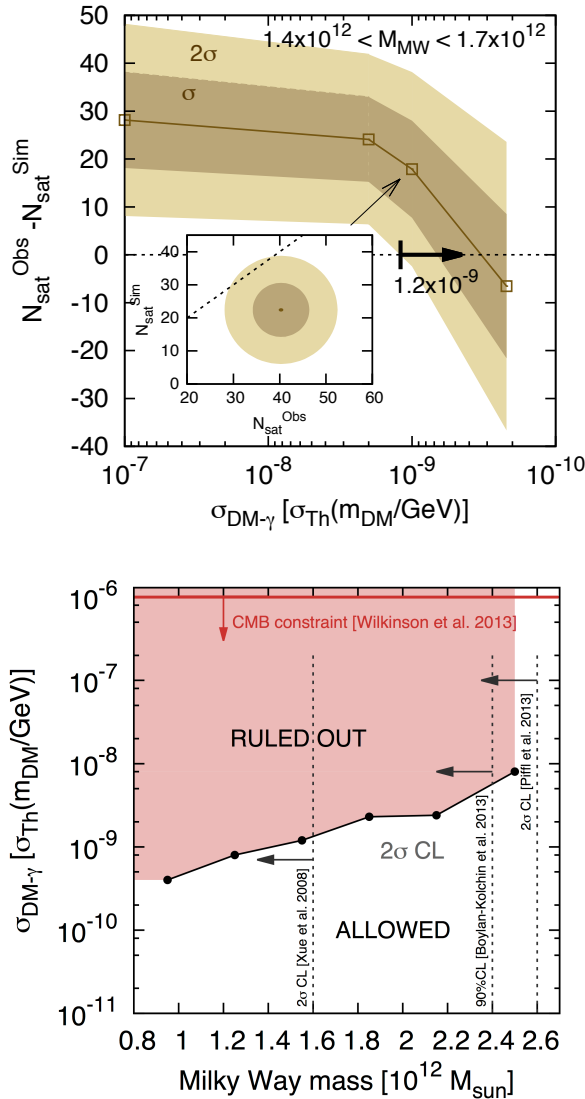


Figure 3. Constraints on the γ CDM cross section: (Top panel) Plot of the over-abundance of satellites vs. the cross section for the MW halo mass bin $(1.4 - 1.7) \times 10^{12} M_{\odot}$, where the shaded bands represent the 1σ and 2σ uncertainties. (Bottom panel) Constraints on the cross section are plotted with respect to the MW halo mass. The most recent CMB constraints (Wilkinson et al. 2013) and selected upper mass bounds for the MW halo are shown for comparison.

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